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VACUUM EXTRUSION OF MT. WRIGHT IRON ORE WITH ORGANIC POLYMERS AND BENTONITE AS PLASTICIZER

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by

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ABSTRACT

In this paper the results obtained by laboratory scale tests for the extrusion of iron ore from Mt. Wright containing bentonite and other binders are summarized. It has been demonstrated that pellets can be successfully formed using bentonite and organic binders.

The indurated pellets developed acceptable physical characteristics.

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EXTRUSION À VIDE DE MINERAI DE FER EN UTILISANT DES POLYMÈRES ORGANIQUES ET DE LA BENTONITE COMME PLASTIFIANT

par

D.H.H. Quon* et K.E. Bell**

RÉSUMÉ

Le présent rapport donne un aperçu des résultats obtenus lors d'essais en laboratoire portant sur l'extrusion du minerai de fer en provenance du Mont Wright et contenant de la bentonite et autres liants. Les résultats des essais indiquent qu'il est possible de former des boulettes en utilisant de la bentonite et des liants organiques.

Les boulettes soumises à un durcissement ont acquis des caractéristiques physiques acceptables.

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INTRODUCTION

The agglomeration of iron ore by pelletizing accounts for major iron ore production in North America. The production of iron ore pellets is usually performed in a disc or drum pelletizer by mixing iron ore fines with 0.5 to 2% bentonite together with the required amount of water for balling. The dried green pellets are then indurated at a temperature of approximately 1300°C. Due to the poor reproducibility of physical properties of pellets produced by balling, a program was initiated at CANMET to develop new techniques in iron ore agglomeration. In recent years, a number of new pelletizing processes have been proposed or developed in which air setting of cement clinker or the reaction of lime with steam and carbon dioxide is used to impart strength. Only the Grangcold process, which uses cement clinker, has been developed to the stage of commercial operation (1-6). In these processes bentonite is not required. Another process, different from the cold bonding process, and known as vacuum extrusion, was developed by the Ontario Research Foundation is early 1950 (7). Some iron ore producers have adopted this process to agglomerate iron ore in the United States and England on a pilot scale basis (7-10). A particular advantage of this process is that materials can be shaped from soft and even pasty mixtures with little change in density and thus enable production of pellets with uniform physical characteristics. This paper will focus on the use of organic and inorganic binders or binder systems used for the vacuum extrusion of iron ores.

GENERAL CHARACTERISTICS OF BINDERS

Bentonite is unquestionably one of the most efficient and cost effective low- and high-temperature binders for pelletizing iron ore. It provides sufficient green and fired strength to the pellets. In the extrusion process, bentonite also serves as a plasticizer as an aid for extrusion. There are very few inorganic binders having physical properties like bentonite. The precise mechanism by which bentonite improves ball strength and the physical properties that make a particular bentonite a good binder have not been completely resolved. Bentonites consist largely

of the clay mineral montmorillonite, are characteristically colloidal, highly plastic and usually have the ability to swell to several times their diameter upon absorbing water. Attempts to correlate the colloid content, the viscosity of standard aqueous bentonite slurries, the electrokinetic charge, pH and chemical composition with the binding properties of a range of bentonite have indicated that the electrokinetic charge and colloid content, considered together, give a useful guide. To its detriment, bentonite carries with it impurities, particularly silica, which is undesirable as it increases the difficulty and cost of smelting the ore.

A variety of inorganic binders have been used as plasticizers and to provide green strength for clay-free materials so that bodies can be molded into desirable shapes before firing. These binders have been used extensively in ceramics processing, including dry pressing, extrusion, tape casting, injection molding and compression molding. A description of the various binders has been documented in the literature (11-20). They were classified based on their origin, chemical composition, physical characteristics, molecular weight, polarity, affinity for water, and dominant adhesion mechanisms.

Consideration of the suitability of the various available binders that may be used for iron ore extrusion yields requirements that the binders be readily soluble or dispersed in a liquid, either organic or water, and be free from substances that would contaminate the iron ore. A uniform dispersion in the liquid phase is important for distributing the binder throughout the particulates to provide uniform plasticity for extrusion. Dry green strength in the body is developed by the evaporation of the liquid; the binder is retained in the body and provides organic bridges between particles.

For the preliminary work reported here, a modicum of bentonite was added to the iron ore to ensure minimally acceptable extrusion behavior and dry and fired strengths. A variety of plasticizer/binder materials were added to evaluate their capacity to improve forming behaviour and dry and indurated strengths, and thus their potential as replacement for bentonite.

EXPERIMENTAL PROCEDURE

RAW MATERIALS

The iron oxide used for the experimental work was obtained from Mt. Wright, Quebec. The concentrates were composed of essentially specular hematite with traces of magnetite, feldspar and quartz.

Bentonite was used as a plasticizer and high- and low-temperature binder. Sodium-substituted bentonite was added to the iron ore at 1.5 mass %.

Other inorganic binders used for the experimental work included sodium carbonate, calcium carbonate, gypsum, calcium hydroxide, calcium oxide and Nyacol (a colloidal silicate). The amount of these additives used is normally less than 3 mass %.

The organic binders employed in this study were: lignosulphonates (Lignosol SF, TSD and XAF), starch, acrylics, sodium carboxymethylcellulose (CMC), methylcellulose (MC), hydroxyethylcellulose (HEC), sodium and ammonium alginates, Elvanol, stearic acid, latex, lactose, and Liqui-Lass (a condensation product of sorbose and polyethylene oxide). Table I give a list of binders and plasticizers used for the experimental work.

The plasticity of mixtures containing iron ore, bentonite and other binders was determined using a Brabender Plastograph (Fig. 1). Essentially, this instrument is composed of a double-shafted pugmill, with the shafts driven differentially by a constant-speed motor through a dynamometer, with means to both indicate and record the torque, in metre. grams, required to overcome the resistance to the shearing action of the blades through the iron ore paste in the mixer. To conduct plasticity measurements, the mixer was filled with 400 g of dry material to a level that, when wet, was halfway up the shafts, which provides the most efficient mixing. Water was then added at a controlled rate of 1.0 mass% of dry iron ore per min. These dynamic conditions produce a rising curve of increasing resistance to shear with increasing plastic strength that eventually peaks and then falls off as the material becomes soft and more easily sheared. Extrusion of clay bricks requires a minimum peak height of 600 to 650 m.g although, given a sufficiently powerful extruder, materials with this inherent level of plasticity can be successfully extruded with less than the indicated water content (21). Factors affecting plasticity

that are considered include amounts of binder and binder combinations, and the water content to produce optimum consistency for extrusion. For successful extrusion, the consistency value is high: the term consistency is a measure of the plastic viscosity of the flowing plastic mass.

Only binders or binder systems that developed high consistency, as indicated by the plasticity determination, were considered for the extrusion experiments. Appropriate amounts of the constituents were then weighed and mixed with the required amount of water in a blender until a uniform dispersion of the individual components in the mix was obtained.

Extrusion work was conducted in two types of vacuum extruders. Preliminary evaluation of extrusion behaviour was performed using a piston type of extruder, where the amount of mixture used was less than 500 g (Fig. 2). An auger type of extruder was then used to evaluate batches of more than 4 kg of the more promising mixtures (Fig. 3). Extrusion was conducted in vacuum, maintained at about 63 cm of Hg, to remove the occluded air. The die used for the piston type extruder was square, 2.5 x 2.5 cm. The auger extruder was fitted with a three-hole die having hole diameters of about 2.54 cm. A hand bow fitted with a piano wire was used to cut the desirable cylindrical pellet length as the mixture was extruded from the die.

The pellets formed by extrusion were dried in an oven for 24 h, at 120°C. The crushing strength of the dried pellets was determined. Some of the oven-dried pellets were then indurated in a resistance furnace at temperatures from 950 to 1300°C with soaking periods from 10 to 20 minutes. The rate of heating for the pellets from room temperature to the induration temperature was normally less than 10 minutes. On completion of the induration cycle, the pellets were removed from the furnace and covered by mineral fibre to reduce the thermal shock due to a rapid rate of cooling. Following cooling, the crushing strength of the pellets was determined.

The induration behaviour of the pellets was also examined using a Zeiss Heating Microscope, and the reaction of the binder with the iron oxide at different temperatures was determined using differential thermal analysis (DTA).

The microstructure of the indurated pellets was examined using an optical microscope.

RESULTS

PLASTICITY DETERMINATION OF IRON ORE WITH BENTONITE AND/OR ORGANIC PLASTICIZERS

The consistency of the specular hematite from Mt. Wright shows a maximum value of 290 m-g of torque at a water content of 11 mass% as determined by the Plastograph. Additions of bentonite increased the consistency in proportion to the mass% of bentonite added (Fig. 4). Trial extrusions, using the piston-type extruder, established that the minimum consistency for successful extrusion was about 450 m-g of torque, corresponding to a bentonite addition of 1.5 mass%.

A further search for suitable binder-bentonite systems was conducted based on plastograph determinations. Due to the high cost of the other binders, a 1.5 mass% bentonite addition was chosen as the basic binder and plasticizer. Other organic or inorganic binders were then added to the iron ore and bentonite mixture, in amounts normally less than 1 mass%, to improve the plasticity for extrusion. Iron ore containing 0.25 mass% methylcellulose and 1.5 mass% bentonite additions developed a consistency of 660 m-g of torque. The consistency values of iron ore containing bentonite and other binders are given in Table 2. It can be seen that some of the binder systems are capable of significantly modifying the plastic behaviour of the iron ore and bentonite. Other binders or binder systems evaluated, such as lignosulphonates, guanidine, urea, Elvanol, Nyacol, latex and some acrylic binders, showed very little effect in modifying the plasticity of the iron ore at low additive concentration. Based on the consistency determination, it has been shown that binders such as MC, HEC, CMC, alginate and some acrylics are capable of modifying the plasticity of the iron ore significantly, even with low binder concentration. The effect of 0.25 mass% of selected organic binders in addition to 1.5 mass% bentonite on the plasticity of the iron ore is shown in Fig. 5.

During the extrusion work, it was noted that iron ore can be extruded readily with certain binder combinations and retains its shape, whereas others can be extruded but tend to deform due to high water content. Extrudates containing MC and bentonite have a tendency for water to separate from the iron ore particulates and the binder under pressure, resulting in a decrease of water content in the pellets. On the other

hand, extrudates containing alginate and bentonite as binders retain more water and produce pellets that are readily deformed by the drop test. Of the various organic binders used for plasticizing the iron ore, best extrudates were obtained from mixtures containing 0.25 mass % HEC and 1.5 mass % bentonite. Cellulose-based material such as carboxymethylcellulose and methylcellulose show similar plasticity or extrusion behaviour. Alginate-based binders are suitable for the extrusion work, however the plasticity modification of the iron ore is slightly less than for the cellulose binders.

PELLET EXTRUSION

Extrusion of the iron ore was conducted only for mixtures that developed adequate consistency, as indicated by the Plastograph. Early extrusion trials clearly indicated that a consistency of 450 m.g of torque is required for the extrusion of this iron ore using either a piston or auger type extruder. Trials were made from mixtures containing 1.5 mass % bentonite and variable amounts of the organic binders together with the iron ore and the required amount of water from a piston type extruder. Pellets can be extruded without difficulty with mixtures containing a 0.25 mass % of organic binders such as MC, CMC, HEC and alginate. Extrusion of pellets was unsuccessful using a 0.5 mass % acrylic based binder (Acrysol G110), but by increasing the binder concentration to 1 mass %, pellets were formed from the extruder without much difficulty. It appears that organic binders of low viscosity at low levels of addition are not capable of sufficiently modifying the plasticity of the iron ore, even in the presence of 1.5 mass % bentonite. The disadvantage of using high levels of organic additive is their high cost and as a result work was centered mainly on organic binder additive concentrations of less than 0.5 mass %. A summary of the extrusion behaviour of several trials using the auger extruder is given in Table 3.

Extruded green pellets with high moisture content do not rupture in the drop test but, rather, deform plastically. The dry compressive strengths of extruded pellets containing different binders are given in Table 4, and show a minimum of 140 N and a maximum of 774 N. The dry strength is lower for mixtures containing HEC binder and MC with $Ca(OH)_2$. Dry strength development appears related to both the binder or binder system used and to the moisture content of the green pellets.

PELLET INDURATION

Figure 6 gives the DTA curves for the oven dried pellets containing 1.5 mass % bentonite and 0.25 mass % organic binder. These curves show that the organic binder decomposes at a temperature well below 400°C, as indicated by the strong exothermic peak at around 300°C. The endothermic peaks at 570 and 680°C are attributed to the inversion of quartz and to the ferromagnetic transition of the iron oxide, respectively.

Typical extruded pellets after oven drying are shown in Fig. 7. These dry pellets are highly impact resistant and can be handled with ease during transport. In the induration process, care was taken to avoid too rapid decomposition of the organic binder by heating too rapidly at low temperature, which could result in bloating of the pellets. Thus the temperature was held first at below 400°C to allow the volatiles to escape. On completion of the binder burn-off, the pellets were introduced into the induration zone. Bloating or swelling of the pellets under these conditions was never observed.

Compressive strengths of the pellets containing 2 mass % bentonite and 1.5 mass % bentonite with organic binder addition, indurated at various temperatures for 10 minutes and for 20 minutes, are given in Table 4, and selected data are plotted in Fig. 8 and 9. Pellets containing 2 mass % bentonite developed a strength of 2280 N at 1150°C for 10 minutes (Fig. 8). A similar strength development was observed for pellets containing 1.5 mass % bentonite and 0.25-0.5 mass % organic binder, for which, with the exception of pellets containing alginate, a strength of 2000 N can be obtained by induration at 1250°C for 10 minutes. It is notable that pellets containing 2 mass % bentonite reach equivalent strength at a temperature 100°C lower. For a soak time of 20 minutes, pellet strengths of about 2000 N were obtained for different binders and binder systems at about 1150°C, as shown in Fig. 9. Furthermore the strengths continued to increase with induration temperature. The strengths for extrudates containing alginate are lower than for the extrudates containing other binders. Pellets containing MC, HEC and CMC showed strength development very similar to each other. Pellets containing 2 mass % bentonite developd equivalent strength at a temperature lower by about 75°C.

In order to determine the effect of organic binder quantity on the strength development of the pellets, 0.25 and 0.5 mass % alginate additions

were made to the iron ore containing 1.5 mass % bentonite. Extruded pellets from these mixtures were indurated at different temperatures and times. The results of the strength development for these pellets for induration temperatures of 950 to 1250°C with a 20 minutes soak time are plotted in Fig. 10, and indicate that higher strengths are generally developed where additive concentration increases.

Induration of extrudates containing 1 mass % bentonite, 1 mass % $Ca(OH)_2$ and 0.125 mass % MC was conducted. The strength development of these pellets is plotted in Fig. 11 as a function of induration temperature and time. The results show that the strength developed to its maximum at above 1100°C with a soak time of 20 minutes, and 1200°C with a soak time of 10 minutes.

MICROSTRUCTURE OF THE INDURATED PELLETS

Optical microscopy was used to examine the indurated pellets. The resulting microstructures for pellets indurated at 1300°C for 20 min are shown in Fig. 12 to 15. No appreciable difference in microstructure was observed for pellets containing different types of organic binders. A common characteristic of the microstructure is scattered coarse platelets of specular hematite oriented in the (0001) crystallographic direction, with fine-grained hematite occurring at the interstices. Evidence of neck-growth is observed in the fine-grained material. The irregular shape of the platelets revealed that very little, if any modification took place at high induration temperature. No evidence was seen of a slag phase being developed and, therefore, the bonding of the grains is due mainly to neck growth.

Under identical induration conditions, slag bonding was observed in samples containing $Ca(OH)_2$ as an additive in addition to the bentonite and MC binder. The microstructure of the sample, shown in Fig. 16, reveals the rounding of the irregular large platelets of specular hematite, and intergrowth of the fine-grained hematite: this modification of the grains is due to the presence of a liquid phase during induration.

DISCUSSION

The potential use of organic binders for agglomeration of iron ore pellets has been reported and demonstrated by other investigators (22-27). Satisfactory pellets have been produced using a cellulose based polymer (Peridur XC-3*) at levels ranging from 0.1 to 0.4 mass % as a binder completely replacing bentonite. Extensive tests conducted in Cia Vale Do Rio Doce (CVRD) using Peridur for pelletizing iron ore demonstrated the quality of the pellets, showing them to have better physical appearance and physical properties of the fired pellets meeting ISO requirements (28). As pointed out earlier, the use of organic binders reduces flux and coke requirements by eliminating excess impurities in the iron pellets. One of the disadvantages of organic binders is their thermal decomposition at relatively low temperature, which may bear adversely on the physical properties of the fired pellets.

In these studies, the major concern was to extrude iron ore pellets, which is different from the balling process. In the extrusion proces, higher pellet density can be obtained as a result of pressure forming, as compared to the balling technique.

The binders used for this investigation included both organic and inorganic binders, both soluble and insoluble. The binders can strongly affect the rheology of the liquid phase. They increase the viscosity and change the flow characteristics from Newtonian to pseudoplastic in most cases. Also with some binders, gels showing Bingham plastic behaviour can develop under various conditions. The rheology of the solution directly affects the behaviour of suspensions and pastes formed by adding particulates to the solution. It is readily apparent that the applicability of a given binder for a specific process is very dependent on the rheological characteristics of the binder solution.

It has been demonstrated that most inorganic organic binder additives do not modify the plasticity sufficiently under low additive concentration for iron ore extrusion. Of the various binders used, it was found that cellulose-based and alginates met the requirement as low temperature binders, whereas bentonite met the requirement for both low- and high-temperature binders.

For the extrusion work, water soluble polymers were considered. The long-chain molecules of these polymers contain a large number of carboxyl groups and these, depending on the particular application, can be varied with regard to number and spacing; the viscosity of these polymers can also be varied dependent upon the solution concentration. The increase in viscosity of a liquid as large molecules (and colloids) are added is strongly influenced by their shape. The effectiveness of molecules or colloids for increasing viscosity is dependent on its "sphere of influence" in the liquid. Molecules and colloids are constantly in motion (Brownian) because of thermal vibration and impact by the water molecules. For a given molecular weight, a molecule has the largest sphere of influence when it is longer in one direction. Thus a linear molecule has a greater sphere of influence than the branched molecule of equivalent molecular weight.

Organic binders are often arbitrarily designated according to how effectively they increase the viscosity of a solution. The cellulose and alginates are available in medium to high viscosity ranges. The viscosity imparted by the binders is one of the primary considerations in the selection of a binder for a specific process. For the extrusion work, high viscosity liquid is desirable. If the liquid is too fluid, it would be easily squeezed out and separated from the iron ore particulates. The clay-iron ore-water system can readily develop a plastic-like nature. The mechanism involved in this process is that a gel-like substance forms on the surface of the iron ore particle from the reaction of water and clay. The gel provides lubrication so that a dispersion of solid particles may exhibit flow characteristics similar to non-Newtonian fluids. Adding an organic binder to the clay-iron ore system increases the viscosity and thus enables it to lubricate the particulates and to prevent the individual particles from contact. Based on the extrusion work, it appears that cellulose and alginate based binders have a capability similar to bentonite in generating the necessary deformability.

The dry strength for organic binders in combination with bentonite is either higher or lower than for pellets containing bentonite alone. This appears to relate to the amount of water and the concentration of the binder used for the extrusion, and the viscosity of the binder.

The indurated strengths of pellets containing bentonite and organic binder are lower than that of pellets containing only bentonite and this is particularly so when indurated at lower temperatures or shorter soak times. At a higher induration temperature and longer soak time, pellets containing organic binders show only minor differences in strength from those containing only bentonite binder. Pellets containing $Ca(OH)_2$, MC and bentonite as binder developed higher strengths than pellets containing other binders at an induration temperature of 1150°C for 20 min: this is due to the liquid phase bonding resulting from the reaction of the calcium oxide with the silica in the iron ore.

CONCLUSIONS

Preliminary examination of the feasibility of iron ore extrusion has demonstrated that pellets can be shaped using bentonite and organic binders. Of the various organic binders examined, it was observed that the high viscosity celluloses and alginate can be partially substituted for bentonite in quantities as low as 0.25 mass %. It has been demonstrated that the organic binders are capable of modifying the plasticity of the bentonite iron ore mixture to produce sound pellets by extrusion. The indurated pellets developed strengths acceptable under ISO requirements.

The results so far obtained make it highly desirable to continue the tests with the best binder systems for producing extruded pellets. Further tests are necessary to characterize the physical properties of the pellets in terms of pilot scale processes as well as from an economical point of view.

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Table 1. Source and description of products

Product	Chemical Identity	Manufacturer
Acrysol A-3	Polymer	Rohm & Haas
Acrysol G110	Polymer	Rohm & Haas
Acrysol AC-33	Polymer	Rohm & Haas
Alginate (Na)		Kelco
Ammonium acetate		Anachemia
Calcium hydroxide		Fisher Chemical
Calcium carbonate		Fisher Chemical
Calcium oxide		Fisher Chemical
Calcium sulphate dihydrate		Baker
Carboxyl methylcellulose (CMC)		Hercules
Corn starch		Best Food
Elvanol HV	Polyvinyl alcohol	E.I. Dupont deNemours
Guanidine carbonate	$(NH_2C.NHNH_2)_2.H_2CO_3$	Eastman Organic Chemical
Lactose		Fisher Chemical
Lignosol XAF	Lignosulphonate	Lignosol Chemical
Lignosol SF	Lignosulphonate	Lignosol Chemical
Lignosol TSD	Lignosulphonate	Lignosol Chemical
Methocel	Methylcellulose (3000cps)	Dow Chemical
Natrosol (HEC)	Hydroxyl ethylcellulose	Hercules
Nyacol 2050	Colloidal silica	Nyacol Products
Polysar PL404	Latex	Polysar Co.
Polysar PL458	Latex	Polysar Co.
Polysar PL776	Latex	Polysar Co.
Polysar PL989	Latex	Polysar Co.
Rhoplex	Polymer	Rhom & Hass
Sodium carbonate		Anachemia
Stearic acid		Fisher Chemical
Superloid	Ammonium alginate	Kelco Co.
Tween 80	Polyoxyethylene sorbitan monooleate	Anachemia
Urea	H_2NCoNH_2	Fisher Chemical

Table 2. Determination of plasticity for iron ore extrusion

Inorganic Binder, %	Organic Binder, %	Water %	Plasticity, + peak height
1.0 b		11	340
2.0 b		11	450
3.0 b		13	600
4.0 b		12	740
2.0 b(wyo)		12	675
3.0 b(wyo)		12	700
	0.5 lignosulph TSD	9	275
	0.2 lignosulph TSD	7	350
	0.5 lignosulph XAF	11	225
	0.2 lignosulph XAF	11	230
	0.25 methylcellulose	10	750
	0.5 methylcellulose	10	1000
	1.5 methylcellulose	11	1600
1.0 b	0.5 lignosulph SF	9	375
1.5 b 1.5 g		12	475
1.5 b 0.5 g		12	400
1.5 b 1.0 g		13	400
1.5 b 0.5 nc		12	425
1.5 b 1.0 nc		12	400
1.5 b	0.5 carboxylmethycellulose	13	760
1.5 b	0.25 carboxylmethycellulose	12	660
1.5 b	0.5 rhoplex AC33	11	420
1.5 b	0.5 acrysol A3	11	410
1.5 b	0.5 acrysol G110	10	475
1.5 b	1.0 acrysol G110	10	560
1.5 b	1.0 nyacol 2050*	11	360
1.5 b	0.5 acrysol ASE60 Tween 80	12	510
1.5 b	1.5 guanidine	12	335
1.0 b	10.0 flue dust*	11	340
1.5 b	0.5 urea	11	375
1.5 b	1.5 urea	10	375
1.5 b	0.25 elvanol	12	380
1.5 b & 0.5 g		12	400
1.5 b & 1.0 g		13	400
1.5 b & 1.0 sc		12	400
1.5 b & 1.0 wcc		12	400
1.5 b & 0.5 sc		12	425
1.5 b	0.5 lactose	10	410
1.5 b	1.5 corn starch	12	440
2.0 b		11	450
1.5 b	0.5 corn starch	12	450
1.0 b & 1.0 wcc		11	450
1.5 b	0.5 stearic acid	12	450
1.5 b & 1.5 cah		11	460

Table 2. Continued

Inorganic Binder, %	Organic Binder, %	Water %	Plasticity, + peak height
1.5 b	0.25 alginate	11	510
1.5 b	1.0 acrysol G110	10	540
1.5 b	0.125 methylcellulose	15	550
1.5 b	0.25 hydroxyl ethylcellulose	15	600
1.5 b	0.5 alginate	11	605
1.5 b	0.25 methylcellulose	13	660
1.5 b	0.25 carboxyl methylcellulose	12	660

* inorganic binder/plasticizer
b = greek bentonite
nc = sodium carbonate
cah = calcium hydroxide
wcc & sc = clay from Newfoundland
g = gypsum
iron ore with 11% water showing peak height 290 m.g of torque
+ consistency in metre-grams of torque

Table 3. Extrusion of iron ore with bentonite and organic binders

Exp. No.	Binders	Physical Character
1	1.5% bentonite 0.25% alginate 11% water	good wet and dry strength
2	1.5% bentonite 0.5% alginate 11% water	good wet and dry strength, easily extruded
3	2.0% bentonite 12% water	good water retention, poor wet strength
4	1.5% bentonite 0.25% alginate 11% water	good extrusion and fair water retention
5	1.5% bentonite 0.25% alginate 10% water	reduction of water by 1% and shows better retention of water
6	1.5% bentonite 0.25% methylcellulose 13% water	fair to moderate wet strength, water content slightly high
7	1.5% bentonite 0.25% CMC 12% water	easily extruded, good water retention
8	1.5% bentonite 0.25% HEC 14% water	easily extruded, poor water retention and weaker wet strength
9	1.0% bentonite 0.125% methylcellulose 1.0% $Ca(OH)_2$ 13.5% water	easily extruded, poor water retention, weaker wet strength

Table 4. Crushing strength of the indurated pellets

Ext. No.	Binders	Dry strength+, N	Indurated temp °C	time, m	Strength, N
1	1.5% bentonite 0.25% alginate 11% water	490	1250	20	2890
				10	1550
			1150	20	1690
				10	1100
			1050	20	1200
				10	850
			950	20	859
				10	590
2	1.5% bentonite 0.5% alginate 11% water	774	1250	10	2316
				20	3463
			1150	10	1186
				20	2293
			1050	10	1026
				20	2446
			950	10	581
				20	879
3	2.0% bentonite 12% water	506	1250	10	2171
				20	4351
			1150	10	2283
				20	2580
			1050	10	764
				20	1715
			950	10	483
				20	781
4	1.5% bentonite 0.25% alginate 11% water	396	1250	10	1663
				20	2199
			1150	10	951
				20	1650
			1050	10	810
				20	1160
			950	10	366
				20	748
5	1.5% bentonite 0.25% alginate 10% water	442	1300	10	2058
				20	2760
			1250	10	1720
				20	2617
			1150	10	2296
				20	2061
			1050	10	1205
				20	1669
			950	10	595
				20	859

Table 4. Continued

Ext. No.	Binders	Dry strength+, N	Indurated temp °C	time, m	Strength, N
6	1.5% bentonite 0.25% methylcellulose 13% water	574	1300	10	2940
				20	4720
			1250	10	2584
				20	2713
			1150	10	1470
				20	2217
			1050	10	693
				20	1127
			950	10	330
				20	516
7	1.5% bentonite 0.25% carboxylmethylcellulose 12% water	386	1300	10	1813
				20	3393
			1250	10	1895
				20	3087
			1150	10	1163
				20	2303
			1050	10	634
				20	1094
			950	10	444
				20	660
8	1.5% bentonite 0.25% hydroxyl ethylcellulose 14% water	255	1300	10	2940
				20	3904
			1250	10	2254
				20	2685
			1150	10	1026
				20	2003
			1050	10	373
				20	709
			950	10	179
				20	378
9	1.0% bentonite 0.125% methylcellulose 1.0% $Ca(OH)_2$ 13.5% water	140	1250	10	2950
				20	4443
			1150	10	817
				20	4371
				20	5400
			1050	10	532
				20	431
			950	20	248
				10	438

+oven dried at 125°C

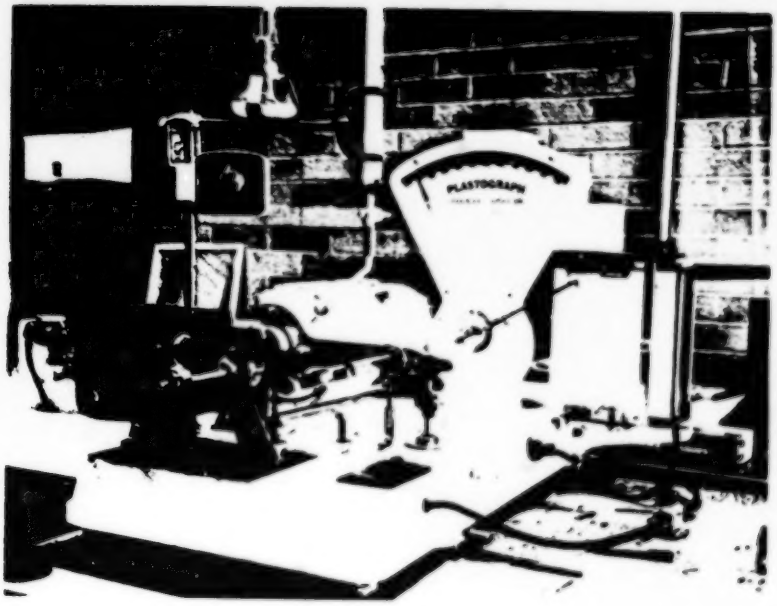

Fig. 1 - Brabender Plastograph used for measuring plasticity of iron ore and binders

Fig. 2 - Piston Extruder used for pellet extrusion

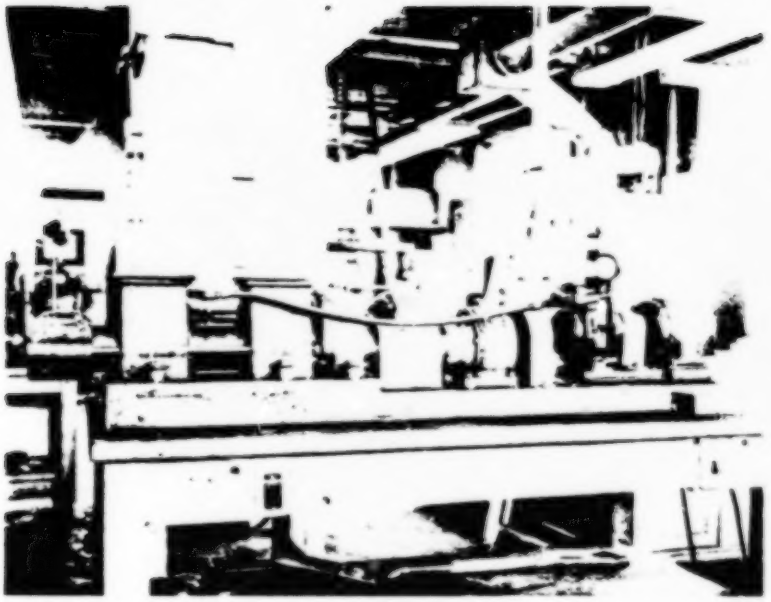

Fig. 3 - Auger Extruder used for pellet extrusion

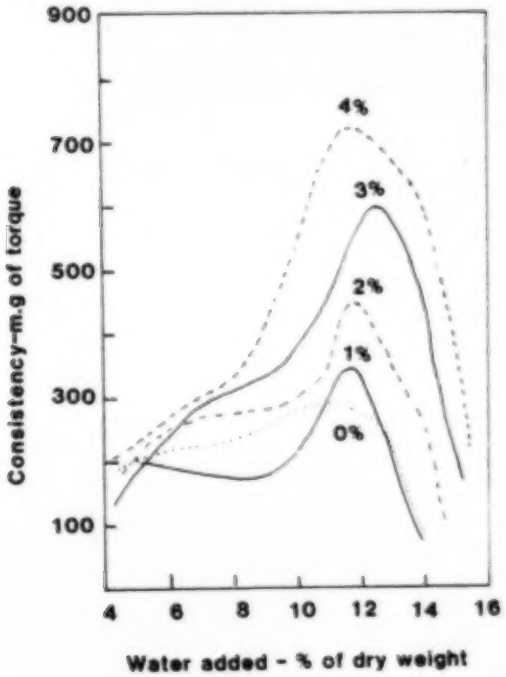

Fig. 4 - Effect of bentonite additions to Mt. Wright iron ore

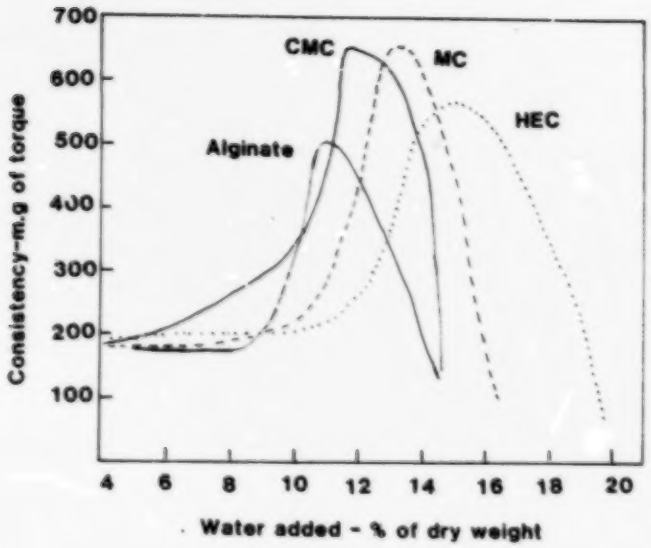

Fig. 5 - Effect of 1.5% bentonite and 0.25% organic binder additions to Mt. Wright iron ore

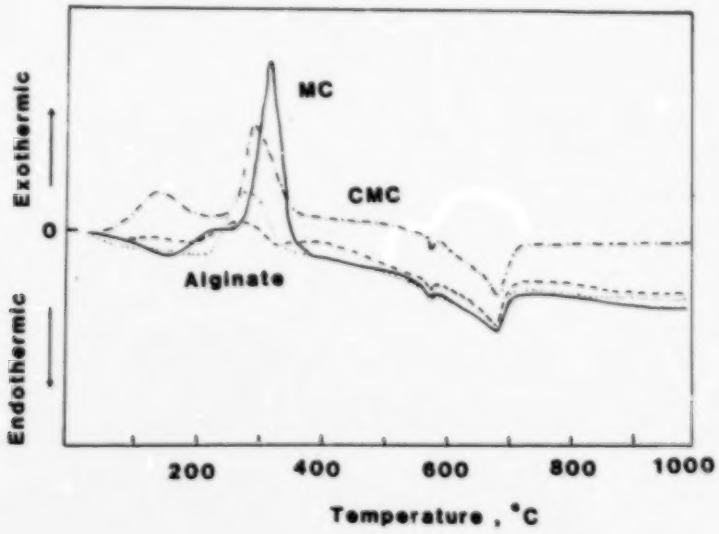

Fig. 6 - DTA curves for 1.5% bentonite, 0.25% organic binder and iron ore

Fig. 7 - Extruded pellets after oven drying at 120°C

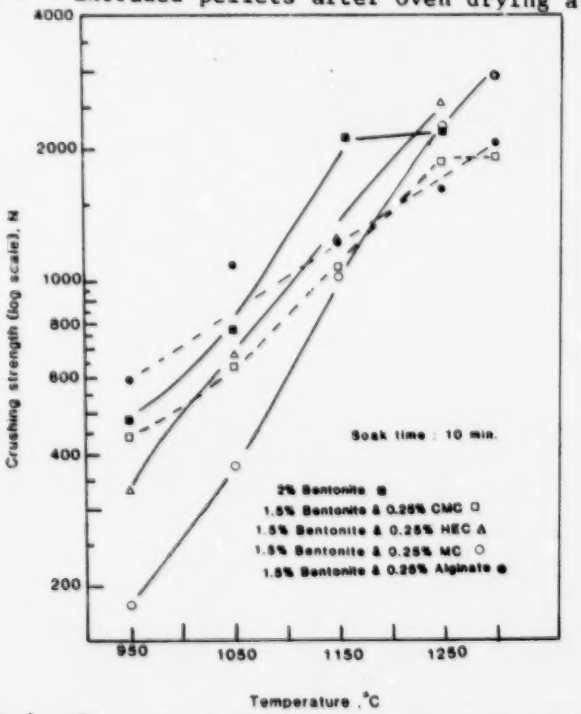

Fig. 8 - Strength development of pellets indurated at different temperatures for 10 min.

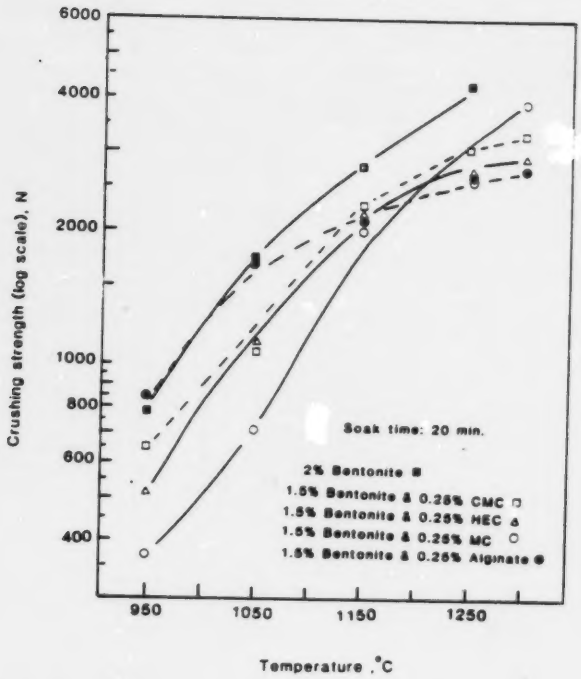

Fig. 9 - Strength development of pellets indurated at different temperatures for 20 min.

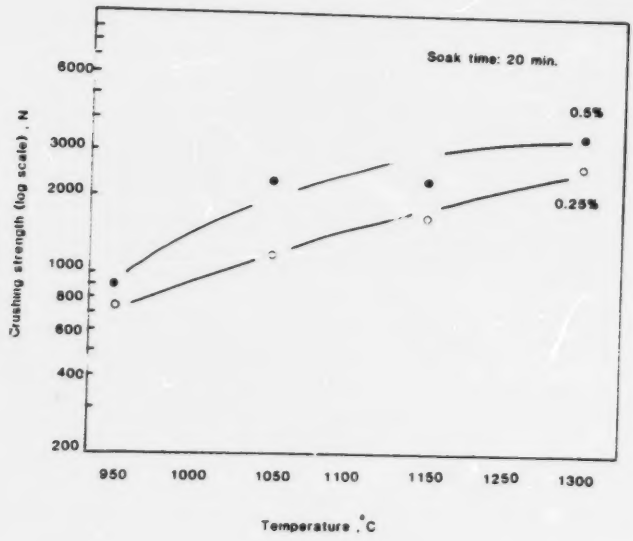

Fig. 10 - Strength development versus additive concentrations indurated at various temperatures for 20 min.

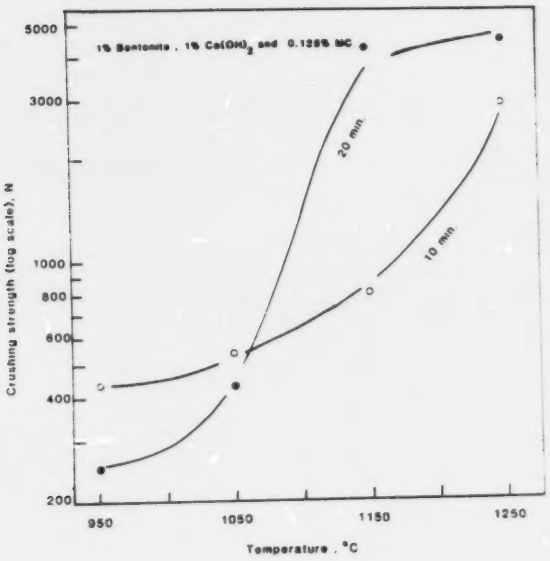

Fig. 11 - Strength development of pellets containing bentonite, calcium hydroxide, and methylcellulose indurated at different temperatures and times

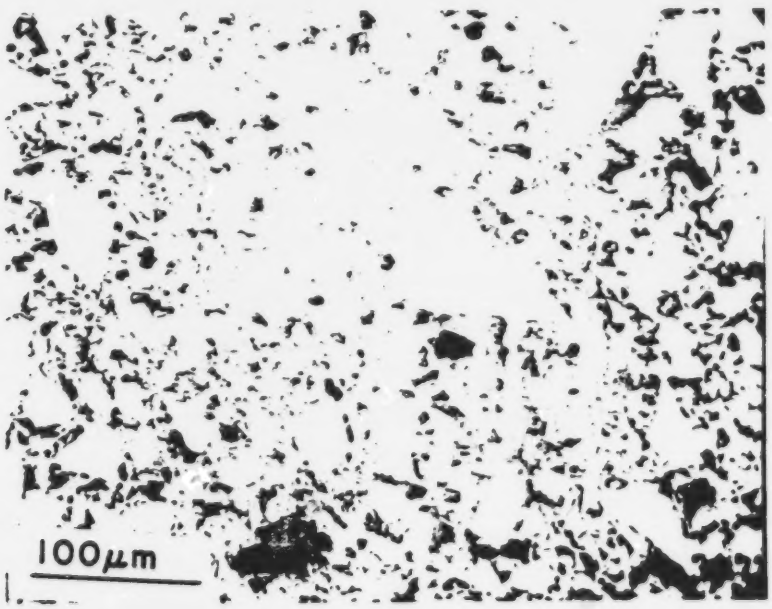

Fig. 12 - Microstructure of pellets containing bentonite and alginate indurated at 1300°C for 20 min.

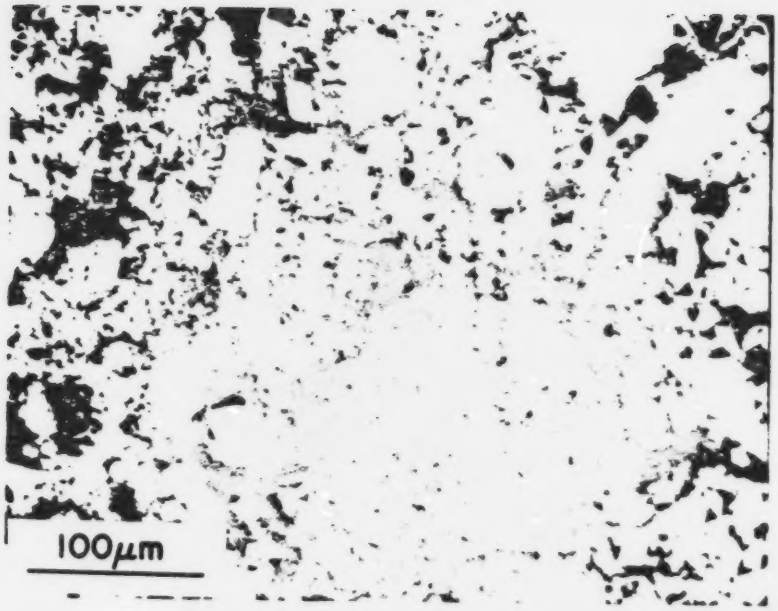

Fig. 13 - Microstructure of pellets containing bentonite and CMC indurated at 1300°C for 20 min.

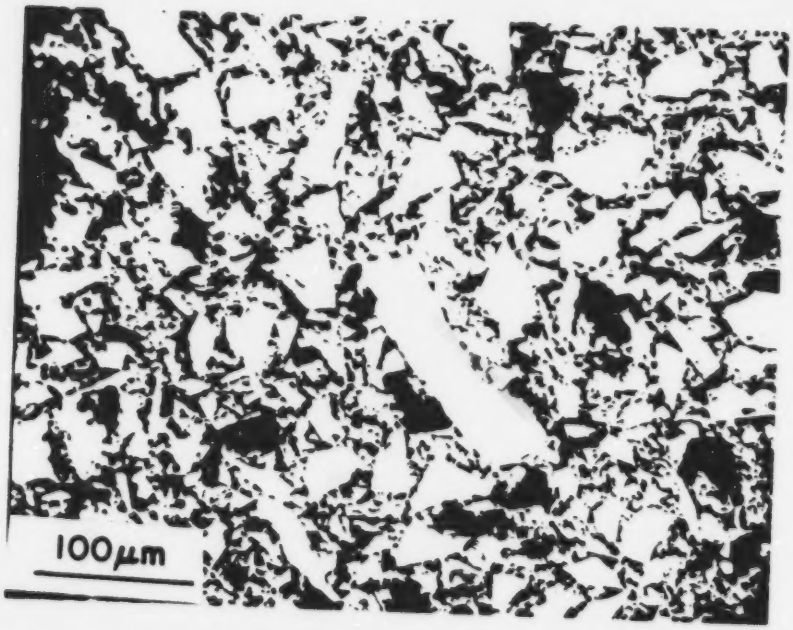

Fig. 14 - Microstructure of pellets containing bentonite and methylcellulose indurated at 1300°C for 20 min.

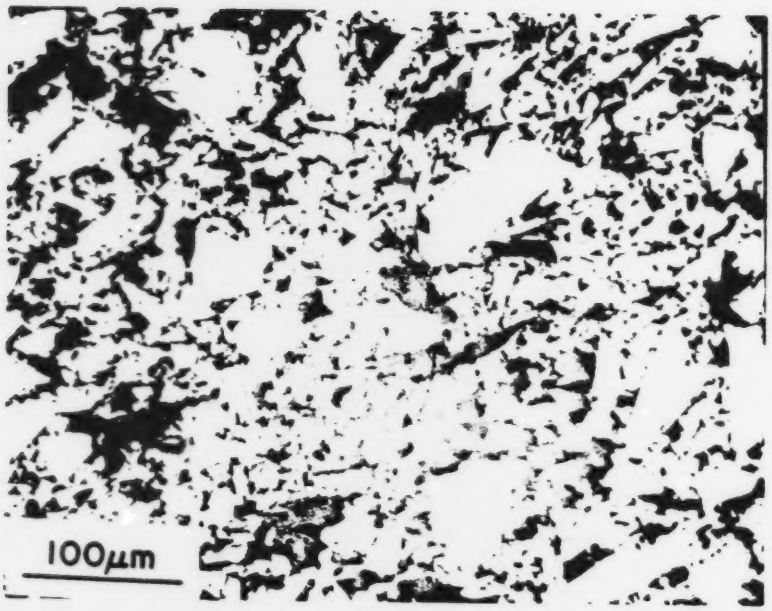

Fig. 15 - Microstructure of pellets containing bentonite and HEC indurated at 1300°C for 20 min.

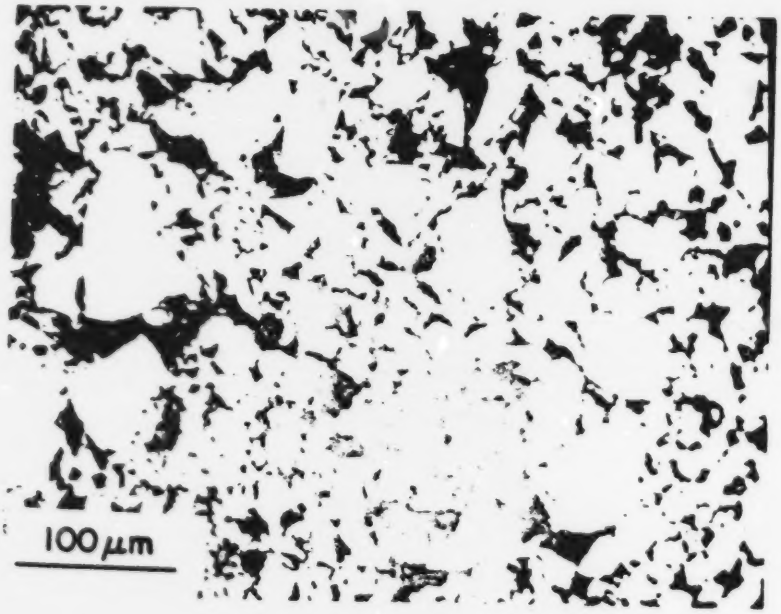

Fig. 16 - Microstructure of pellets containing bentonite, calcium hydroxide and methylcellulose indurated at 1300°C for 20 min.